USAMP Low-Cost Magnesium Sheet Component Development and Demonstration Project

2018 DOE Merit Review Presentation

Presenter and PI :

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United States Automotive Materials Partnership

June 19, 2018

Project ID #mat127

Overview

Timeline

- **Start:** October 1, 2016
- **End:** March 31, 2020
- **Percent complete:** ~30% complete

Budget

Total project funding available

- DOE (70%): $5,651,258
- Contractor (30%): $2,421,968

Funding received in FY17

- DOE share: $520,022
- Contractor share: $222,867

Funding planned for FY18

- DOE share: $2,081,496
- Contractor share: $892,070

Partners

Primary recipient - USAMP LLC – FCA US, Ford, GM

Industry subrecipients

- AET Integration, Inc.
- Fuchs Lubricants Co
- Henkel Corporation
- PPG Industries
- Quaker Chemical Corporation
- Vehma International of America
- Xtalic Corporation

University subrecipients

- The Ohio State University
- University of Florida
- University of Michigan
- University of Illinois at Urbana-Champaign
- University of Pennsylvania

LightMAT national laboratory participants

- Oak Ridge National Laboratory
- Pacific Northwest National Laboratory

Vendors with substantial technical involvement

- Camanoe Associates
- POSCO

Barriers

- High cost of Mg sheet material, and challenges in producing automotive components with it, prevents widespread use in automotive applications
- Lack of adequate predictive tools to enable the low cost manufacturing of lightweight Mg sheet components

Targets

- Overall - 25% vehicle glider mass reduction @ less than $5/lb saved (FOA specific - Mg sheet components at no more than $2.50/lb saved)

Relevance

Overall objective

- Demonstrate the feasibility of producing Mg sheet components with the potential of achieving a fully accounted integrated component cost increase over conventional steel stamped components of no more than $2.50/lb. saved.

Objectives (October 2016 to March 2018)

- Identify and quantify key cost drivers and obstacles associated with current Mg sheet material and automotive component development and manufacturing process.
- Establish a benchmark component cost and weight baseline.
- Using Integrated Computational Materials Engineering (ICME) tools, research, develop, and evaluate at least one new, low cost Mg alloy and commensurate processing configuration(s) suitable for rolling thin, automotive appearance grade sheet, and forming large, challenging automotive panels.
- Evaluate and develop effective, low cost pretreatments/coatings and lubricants, to protect the material from corrosion.

Impact on Barrier(s)

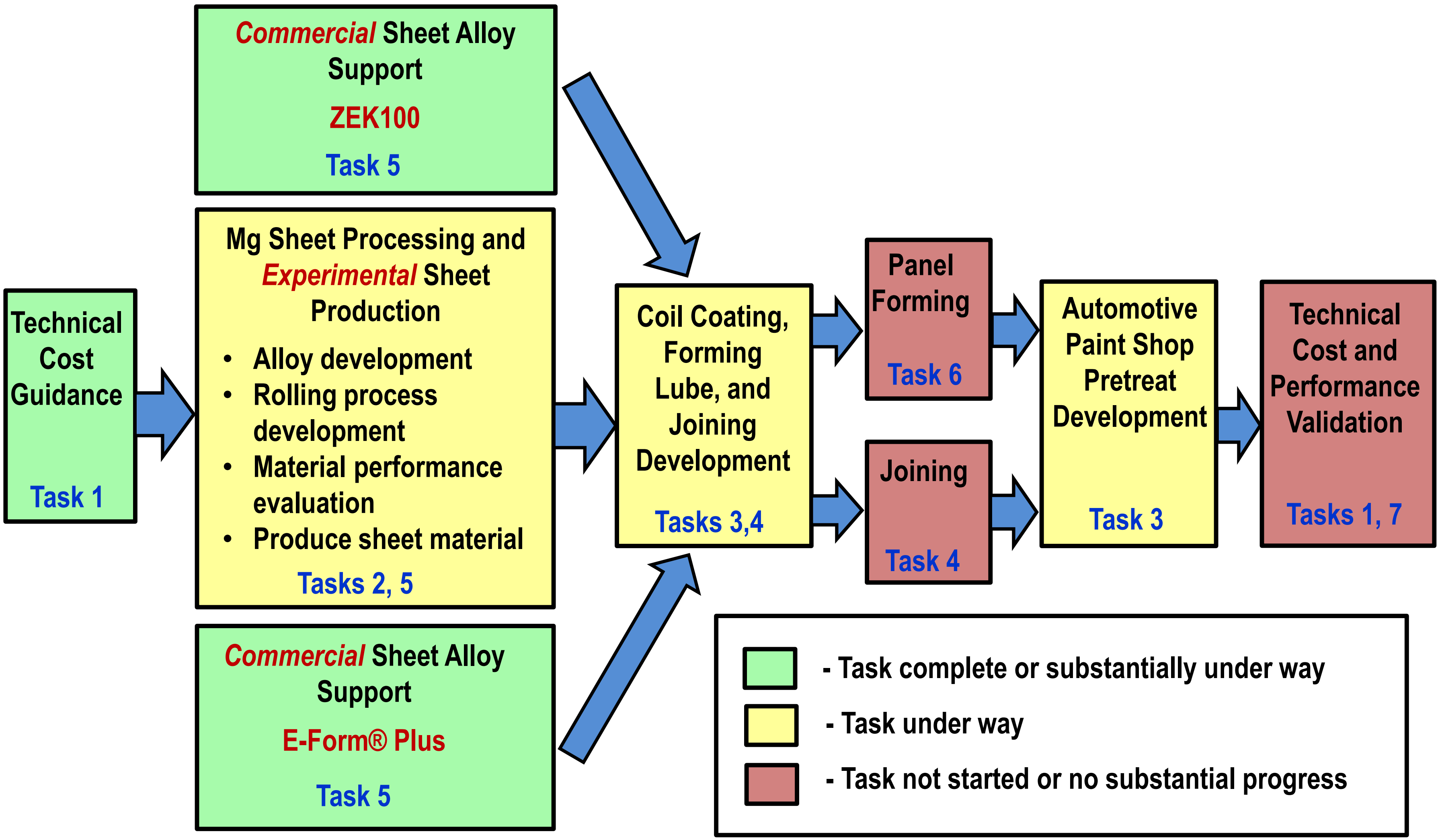
- Demonstrating the feasibility of producing Mg sheet components at a fully accounted integrated component cost increase of no more than $2.50/lb. saved over conventional steel stamped components should help to enable increased use of Mg sheet in automotive applications.
- Improved modeling capabilities to predict behavior of Mg alloys from raw ingot through fully formed and painted automotive component(s) will be developed through collaboration with universities and national laboratories.
- Mg sheet has the potential to substantially reduce mass of automotive components by up to 65% compared to steel (55% projected for this project) and this project is specifically aimed to reduce cost and manufacturing obstacles preventing widespread use of this lightweight material.

Milestones

- The program received a six month no-cost extension for BP1 due to delays in negotiating contracts with subrecipients. The table below reflects that extension:

BP	Milestone Number	Milestone Type	Task	Success Criteria	Due Date	Date Complete	Completion Status
1	1	Go/No Go	**Task 0:** Project Management/Contracting	100% of POs issued to subs	3/30/2018	9/22/2017	**Complete**
	2	Technical	**Task 1:** Technical Cost Guidance	Baseline cost model for Mg sheet complete	3/30/2018	12/22/2017	**Complete**
	3	Technical	**Task 2:** Alloy and Sheet Processing Development	New Mg alloy sheet composition(s) identified	3/30/2018	11/3/2017	**Complete**
2	4	Technical	**Task 2:** Alloy and Sheet Processing Development	Constitutive model for textured Mg-alloy completed and ideal texture suggested	3/30/2019	N/A	10%
	5	Technical	**Task 2:** Alloy and Sheet Processing Development	Forming analysis completed on medium sheet	3/30/2019	N/A	10%
	6	Technical	**Task 3:** Sheet Coatings and Lubricant Evaluation and Development	Forming lubricant composition identified	3/30/2019	N/A	35%
	7	Go/No Go	**Task 5:** Mg-alloy Sheet Production	Manufacture and deliver experimental medium width sheets	3/30/2019	N/A	10%
3	8	Technical	**Task 3:** Sheet Coatings and Lubricant Evaluation and Development	Evaluation of corrosion protection coating completed	3/30/2020	N/A	10%
	9	Technical	**Task 5:** Mg-alloy Sheet Production	Delivery of wide sheet	3/30/2020	N/A	0%
	10	Technical	**Task 6:** Mg-alloy Large Body Component Production	Mg-alloy panels formed to specifications	3/30/2020	N/A	5%
	11	Technical	**Task 7:** Component(s) Demonstration	Final delivery and performance evaluation completed	3/30/2020	N/A	5%

Approach



Technical Cost Guidance
Task 1
Commercial Sheet Alloy Support
ZEK100
Task 5
Mg Sheet Processing and Experimental Sheet Production
• Alloy development
• Rolling process development
• Material performance evaluation
• Produce sheet material
Tasks 2, 5
Commercial Sheet Alloy Support
E-Form® Plus
Task 5
Coil Coating, Forming Lube, and Joining Development
Tasks 3,4
Panel Forming
Task 6
Joining
Task 4
Automotive Paint Shop Pretreat Development
Task 3
Technical Cost and Performance Validation
Tasks 1, 7
- Task complete or substantially under way
- Task under way
- Task not started or no substantial progress

USAMP

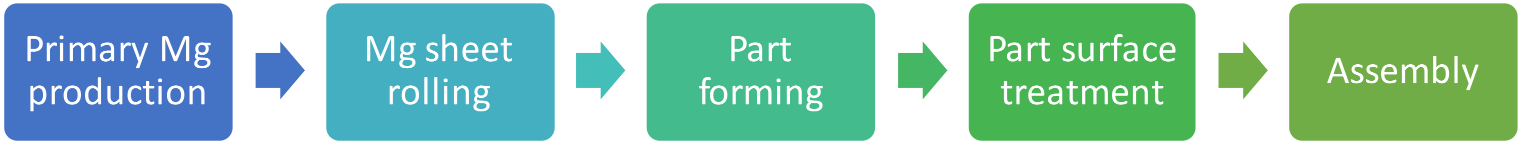
Approach

- Establish a benchmark component cost and weight baseline
- Identify and quantify key cost drivers and obstacles associated with current Mg sheet material and benchmark automotive component development and manufacturing process
- Research, develop, test, and evaluate at least one new, low cost Mg alloy and commensurate processing configuration(s) suitable for rolling thin, automotive appearance grade sheet, and forming large, challenging automotive panels.
- Leverage ICME methods coupled with experimental studies and data tools to define improved alloy chemistry(ies) and thermo-mechanical process development to achieve the following:
  - Improved formability/reduced ***rolling*** and ***forming*** (targeting ~100°C vs. ~250°C for forming of current state of the art commercial alloys) temperatures
  - Mechanical properties sufficient to enable weight reduction opportunities comparable to those of today's Mg sheet materials for the selected automotive components
- Produce/obtain material test samples (both experimental and commercial) to validate ICME predictions for formability and primary and secondary mechanical properties compared to baseline ZEK100 material
- Evaluate and develop effective, low cost pretreatments/coatings, forming lubricants and paint shop coatings
- Evaluate suitable joining processes
- Produce large size sheets for forming automotive component(s)
- Produce and evaluate large automotive components

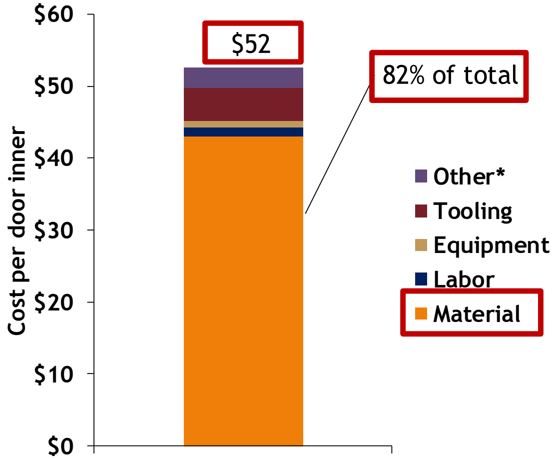
Technical Accomplishments

Technical Cost Guidance

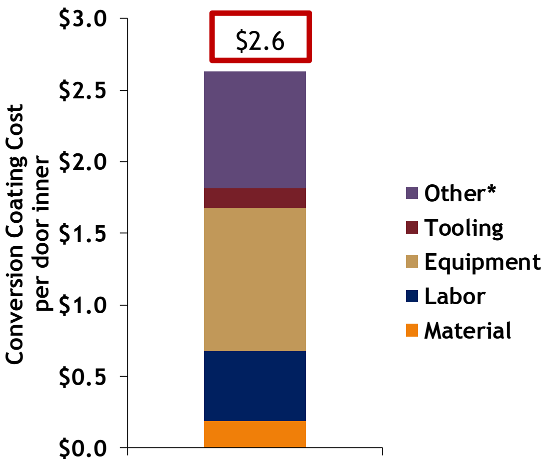
- Identified and quantified major Mg benchmark automotive door panel cost drivers for current process



Current Mg door panel production process



Cost breakdown of warm formed Mg door inner panel



Cost breakdown of conversion coating process for Mg door inner panel

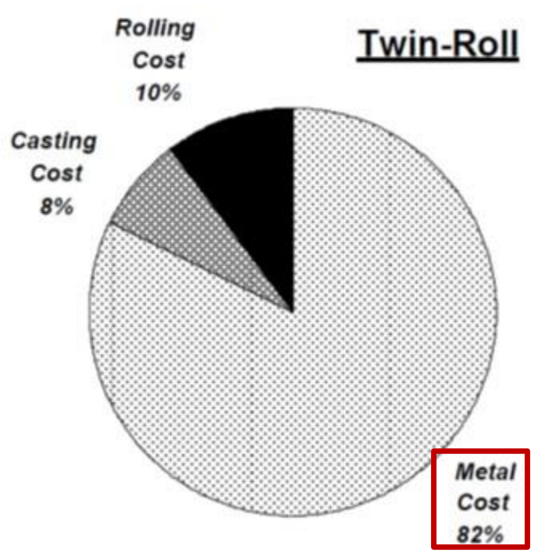
- Clearly, the rolled sheet metal cost is the largest cost driver for the door inner panel

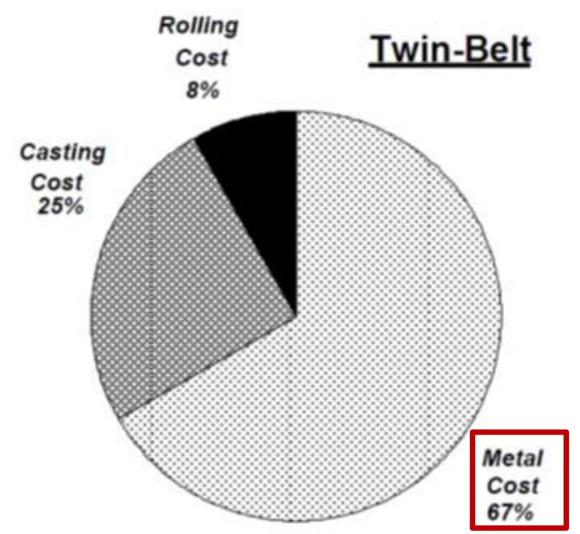
Technical Accomplishments

Technical Cost Guidance

- Compared cost models of two Mg sheet rolling processes (***established*** twin-belt process and ***emerging*** twin-roll process)
  - Twin-roll process is thought to be less expensive because it is less labor and energy-intensive and it is less sensitive to production volume due to lower capital costs
  - Metal cost is the key cost driver for both processes
  - Rolling reduction per pass and recovery are also key cost drivers
  - Cast as close to final thickness as microstructure and surface quality allow
  - Develop alloys and processing schemes to allow 50% reduction per pass without edge cracking

Aluminum Consultants Group (Hunt) and PNNL (Herling) study comparing costs of twin-roll and twin-belt sheet production. Metal cost (AZ31) is primary cost driver in both cases.





- Proposed strip casting process (used in twin-roll process) as a constraint for developing new Mg alloy(s)

Technical Accomplishments

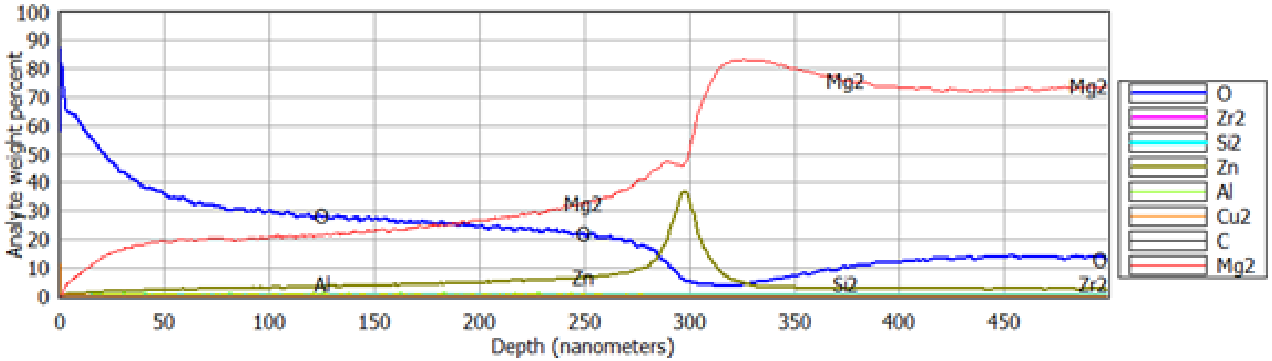
Alloy and Sheet Processing Development

- After evaluation of several Mg alloy chemistries (via literature search, previous experience, and thermodynamic calculations) to identify those with potential for improved performance with reduced rolling and forming temperatures, identified 3 promising new alloys suitable for twin-roll strip casting (lowest cost process), and containing no rare earth addition, for further evaluation and development:
  - Mg-3Al-1Sn-0.3Zn-0.4Mn
  - Mg-2Al-1Sn-0.3Mn
  - Mg-1Al-0.3Ca-0.4Mn
- Down-selected 1 alloy for immediate production of ingot and small experimental sheets to be fabricated at POSCO and evaluated by subrecipients:
  - **Mg-3Al-1Sn-0.3Zn-0.4Mn *(ATMZ3100)***
- Provided, through Korea Magnesium Industry (KMI), new ATMZ3100 alloy ingot for evaluation by project participants and for rolling of narrow lab scale experimental sheet material at POSCO (shown at right).
  - Process refinement for microstructure optimization in progress
  - To be considered for production of medium width (~500-550 mm) sheet in FY18 and potentially for wide width (~1500-1600 mm) sheet in FY19

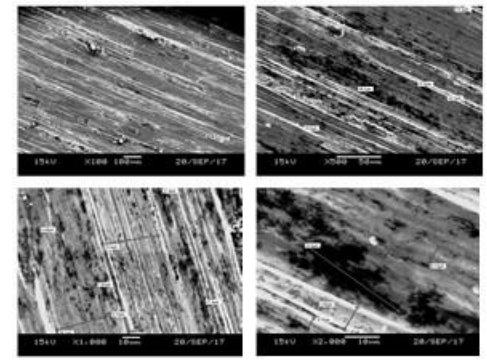
Technical Accomplishments

Coil Applied Coating Development - Henkel

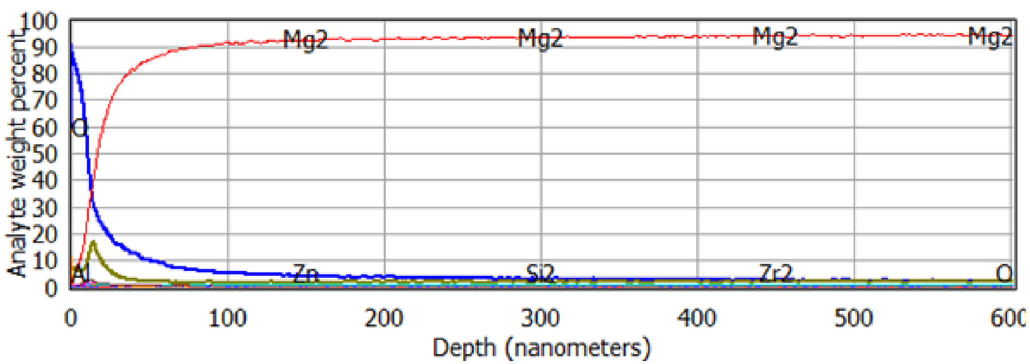
- Evaluated potential coil applied pretreatments to work with current commercially available state of the art Mg sheet alloy (***ZEK100***) and prevent Mg from leaching into E-coat tanks
  - Bare, 6-yr old ZEK100 material showed ~200-300 nm of oxidation, so the first priority was to identify a cleaner/deoxidation process to remove the oxide layer.



GD-OES of ZEK100 Mg Alloy (as received)



SEM images of surfaces of ZEK100 Mg alloy sheet samples showing multiple irregularities and a ridged surface



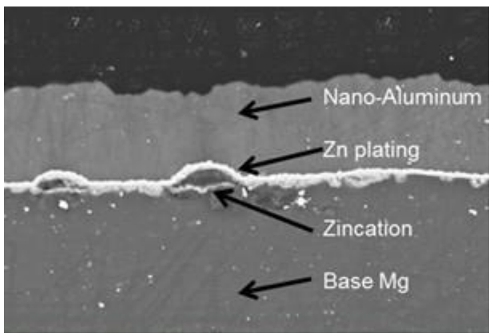
GD-OES for a deoxidized sample of ZEK100 Mg Alloy

ZEK100 sheet before deoxidation (left) and after deoxidation (right)

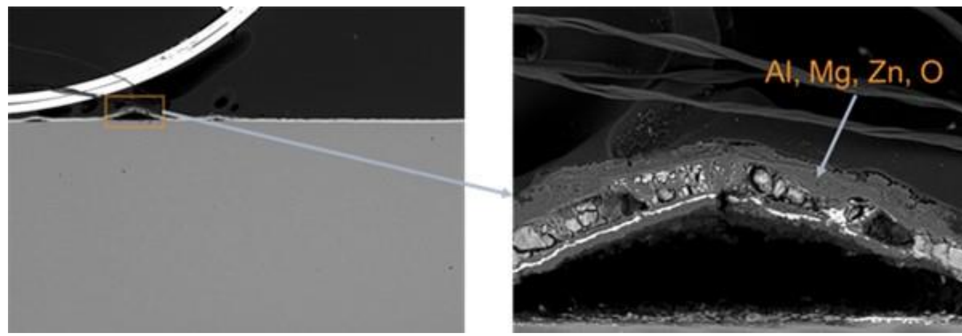
Technical Accomplishments

Coil Applied Coating Development - Xtalic

- Evaluated potential coil applied pretreatments to work with current commercially available state of the art Mg sheet alloys ***(ZEK100***) and ***E-Form Plus*** and prevent Mg from leaching into E-coat tanks
- Created a new pretreatment, using a zincation process followed by a zinc plating process before applying Nano-Aluminum coating to provide corrosion protection for the base Mg substrate
- Small pits from removal of heavy oxide layer from aged ***ZEK100*** lead to porosity in plating
- Al-Mn showed improvement over Al-Zr plating, surviving 160 hrs of ASTM B117 salt spray exposure without pitting on ***ZEK100*** and over 360 hrs on new ***E-form Plus*** material



SEM micrograph of the plated layers on ZEK100.



Trouble spot in the salt spray testing showing overplated Zn layer with corrosion blister evolving from the same location.

Al-Zr **over Mg** ***(ZEK100)*** **showing evidence of corrosion in several spots after** ***96 hours*** **of ASTM B117 salt spray .**

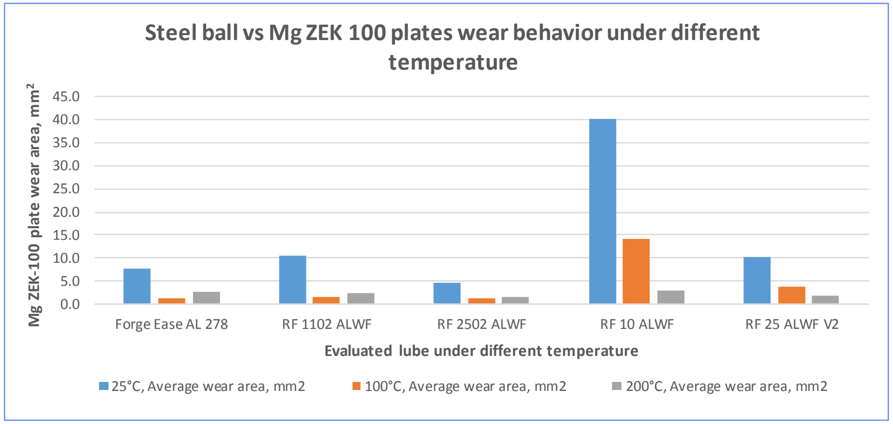
Al-Mn **over Mg** ***(ZEK100)*** **showing no signs of corrosion after** ***65 hours*** **of ASTM B117 salt spray.**

Al-Mn **over Mg** ***(E-Form Plus)*** **showing no signs of corrosion after** ***360 hours*** **of ASTM B117 salt spray .**

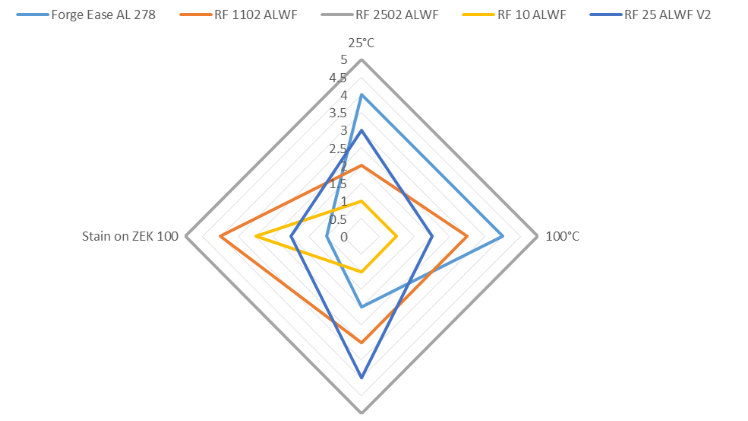
Technical Accomplishments

Warm Forming Lubricant Development - Fuchs

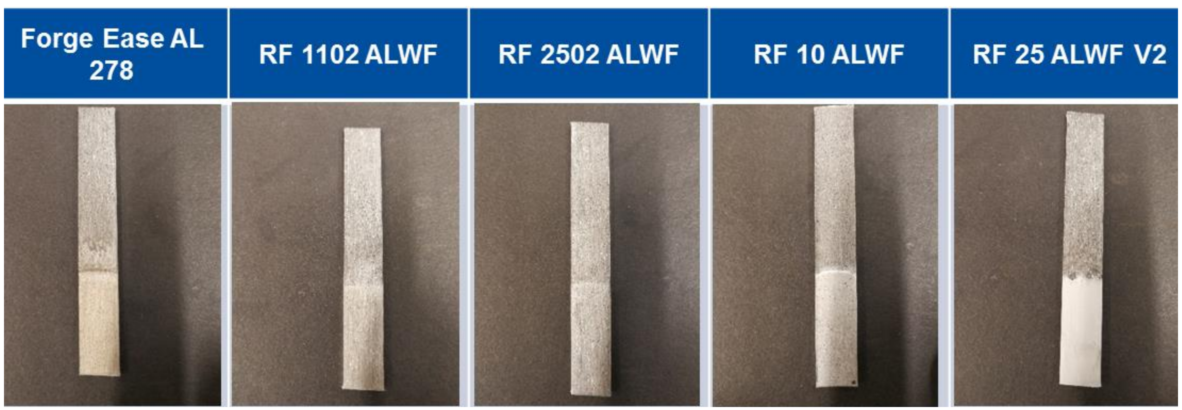
- Evaluated potential lubricants to work with ***ZEK100*** from RT to 250°C that do not need to be cleaned prior to paint process.



Comparison of wear behavior under different temperatures



Lubricants anti-wear & stain properties on Mg alloy ZEK100



Mg ZEK100 strips after being half immersed in a 4:1 mixture of each lube at room temperature for 12 hours

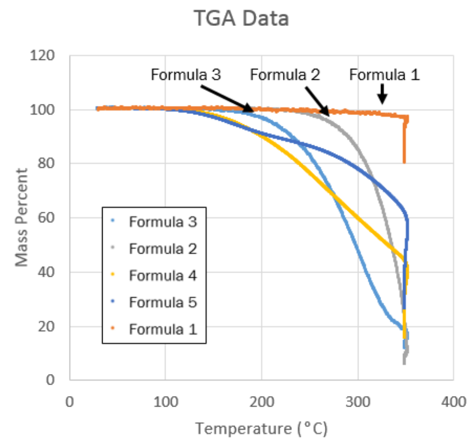
- Early investigation shows RF 2502 ALWF to be the best Fuchs candidate lubricant for use in forming ZEK100 at this time

Technical Accomplishments

Warm Forming Lubricant Development - Quaker

- Evaluated potential lubricants to work with ***ZEK100*** from RT to 250°C that do not need to be cleaned prior to paint process.
- Evaluated 3 potential lubricant formulas to work with ZEK100 using Reciprocating Friction and Wear Test (RCP) at four temperatures between 100° and 250°C
- Formula 1 showed most stable performance for Coefficient of Friction (COF) across the temperature range

Product	Temperature					
	100°C	150°C	200°C	250°C	Across all temps	
	Ave. COF	Ave. COF	Ave. COF	Ave. COF	Ave. COF	Range
Formula 1	0.29	0.31	0.26	0.28	0.285	0.05
Formula 2	0.23	0.24	0.36	0.45	0.32	0.22
Formula 3	0.32	0.35	0.39	0.46	0.38	0.14



- Additional modifications of Formula 1 are currently under evaluation at 100 and 200°C with Twist Compression Tester (TCT)

Figure 3: TCT Data at 100C, 6,000psi, on Mg sheet

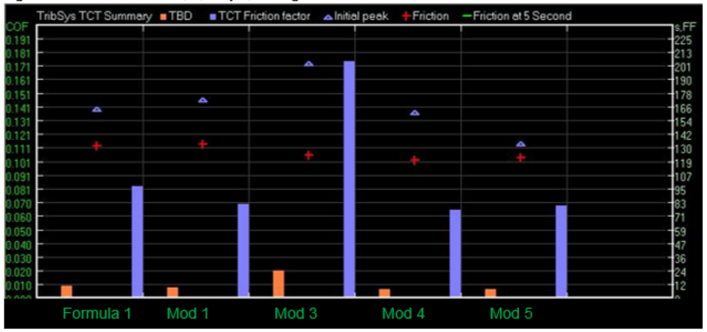
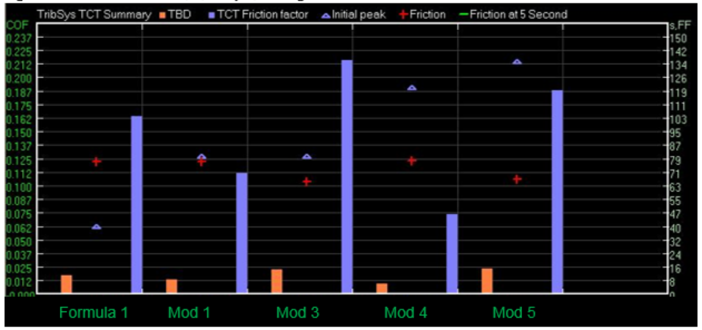


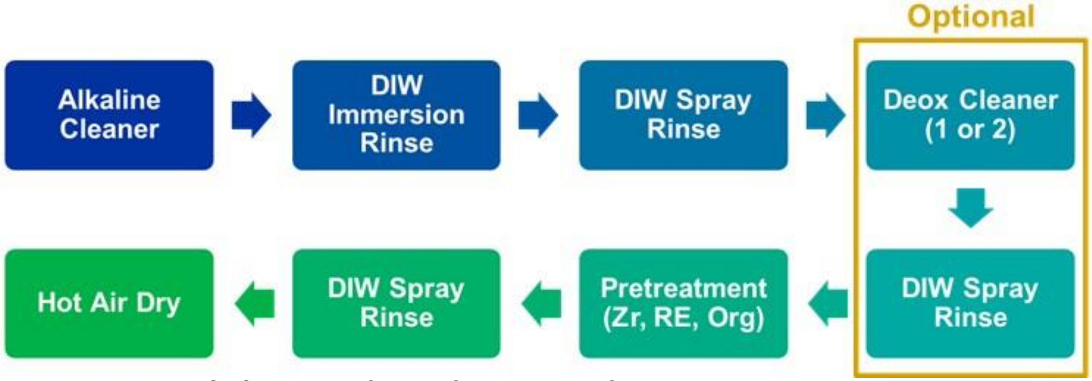
Figure 4: TCT Data at 250C, 3,000 psi, on Mg sheet



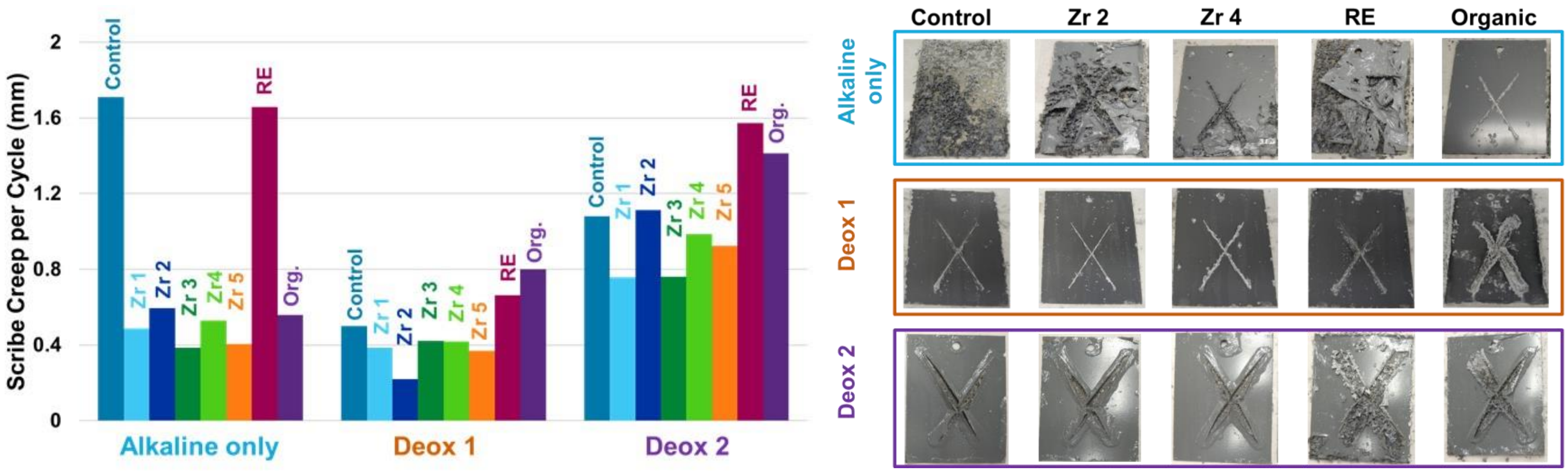
Technical Accomplishments

Paint Shop Applied Coating Development - PPG

- Evaluated potential paint shop pretreatment chemistries to work with ***ZEK100***
  - Organic pretreatments seemed to work best with no deox treatment
  - Zirconium and rare-earth based pretreatments worked best with Deox 1 vs Deox 2



Typical cleaner, deoxidation, and pretreatment process



Scribe creep comparisons of investigated treatments on ZEK100 after 168 hrs ASTM B117 salt spray exposure

Technical Accomplishments

Component(s) Demonstration

- Used CAE tools to evaluate structural performance of 2013 Ford Fusion door inner and outer panels based on commercially available ***ZEK100*** sheet material properties.

- ***55 % mass reduction*** from door inner and outer achieved
- Close to the targets (Ford MMLV side door)
- Further optimization required for dent resistance

#	CAE Assessment		Analysis parameter	Target	USAMP Mg Door CDO-0008
1	Belt line - Stiffness	Inner Belt	Displacement (mm)	Ford MMLV Side Door Performance Targets	
			Stiffness (N/mm)		
		Outer Belt	Displacement (mm)		
			Stiffness (N/mm)		
2	Header - Stiffness		A-Pillar Displacement (mm)		
			A-Pillar Stiffness (N/mm)		
			B-Pillar Displacement (mm)		
			B-Pillar Stiffness (N/mm)		
3	Outer panel - Stiffness		Stiffness (N/mm)		
4	Normal Modes		Door Mode (Hz)		
			Inr Panel Mode (Hz.)		
			Outer Panel Mode (Hz)		
5	Outer panel – Dent Resistance		Permanent set (mm)		
6	Outer panel – Oil Canning		Permanent set (mm)		
7	Vertical door sag		Deflection under Gravity Load (Z mm.)		
			Deflection (Z mm.)		
			Permanent set (Z mm.)		
			Max Plastic Strain		
8	Check over load		Deflection (mag) @ latch (mm)		
			Permanent Set (Mag mm)		
			Max Plastic Strain		

Responses to Previous Years Reviewer Comments

- This project was not reviewed last year.

USAMP Collaboration and Coordination

- Broad participation of domestic OEMs, suppliers and universities (19 responsible for substantial research activities)
- Project executed at task level (7 task teams) and coordinated by a USAMP leadership team

U.S. Partner Organizations

USAMP Leadership Team

FIAT CHRYSLER AUTOMOBILES

Steve Logan, *Principal Investigator*
Randy Gerken
Dajun Zhou
Changqing Du
Jugraj Singh
Kim Tress

Ford

Bita Ghaffari
Mei Li

GM

Jon Carter
Anil Sachdev
Raj Mishra
Lou Hector

M-TECH INTERNATIONAL LLC

Manish Mehta, *Technical Project Manager*

Collaboration and Coordination

Organization	Responsibility
Industry subrecipients (7)	
AET Integration, Inc.	– Joining process evaluation
Fuchs Lubricants Co	– Development of forming lubricants for temps up to 250^{o}C
Henkel Corporation	– Development of coil applied anti-corrosion treatments
PPG Industries	– Development of paint shop applied anti-corrosion coatings for Mg components
Quaker Chemical Corporation	– Development of forming lubricants for temps up to 250^{o}C
Vehma International of America	– Production (stamping) of large Mg components
Xtalic Corporation	– Develop coil applied aluminum plating for Mg corrosion protection
University subrecipients (5)	
The Ohio State University	– Mg alloy design, evaluation, and validation.
University of Florida	– Provide Mg thermodynamic and kinetic data for alloy development
University of Illinois at Urbana-Champaign	– Atomistic modeling for Mg crystal plasticity model development
University of Michigan	– Precipitate evolution and dynamic recrystallization characterization and modeling
University of Pennsylvania	– Develop constitutive model for textured Mg-alloy sheets, FE material user subroutine, drawing and formability simulations, and determine forming limits
LightMAT National laboratory subrecipients – (2)	
Oak Ridge National Laboratories (ORNL)	– Development of optimized Mg sheet rolling process parameters and production of Mg strips for material model calibration and validation
Pacific Northwest National Laboratories (PNNL)	– Mg forming model development, data management, and mechanical properties characterization
Vendors (2)	
Camanoe Associates	– Technical cost analysis and guidance
POSCO	– Production of large and medium width Mg sheet

Remaining Challenges and Barriers

- Rolling and formability performance of experimental alloy must be validated prior to trial production of commercial width sheet
- Medium width experimental sheet must be produced to support development of coatings, forming lubricants, and joining processes
- Coatings, forming lubricants, and joining processes must be finalized and validated on experimental sheet
- New alloy must be characterized for formability and physical and mechanical properties to support forming simulation and structural design before producing door panels
- Structural performance and appearance must be physically validated from door panels formed from the new alloy
- Technical cost evaluations must be conducted once the new alloy and its rolling, coating, forming lubes, joining processes and forming processes are finalized for comparison to a) existing steel door panels, and b) current Mg sheet processes

Proposed Future Research

*** Any proposed future work is subject to change based on funding levels ***

- Proposed Future Work – **FY 2018**
  - Validate ICME predictions for formability and primary and secondary mechanical properties
    - Constitutive model for textured Mg-alloy completed and ideal texture suggested ***(Milestone 4)***
    - Forming analysis completed on medium width sheet ***(Milestone 5)***
    - Produce and evaluate new rare earth free alloys containing <0.2wt% Zr to accomplish grain refinement and texture randomization without using strip-casting technology
  - Produce and deliver medium width Mg sheet material from the experimental alloy (expected to be Mg-3Al-1Sn-0.3Zn-0.4Mn or a variation) for evaluation and performance comparison with ZEK100 and E-Form Plus ***(Milestone 7)***
  - Continue development of low cost coil applied pretreatments, lubricants, and coatings with ZEK100 material and adapt work to E-Form Plus and one experimental alloy
    - Forming lubricant composition identified ***(Milestone 6)***
  - Evaluate suitable joining processes
- Proposed Future Work – **FY 2019**
  - Evaluate performance and cost of alloy, rolling process, coatings, treatments, lubes, etc. for comparison to current commercial alloys and processes ***(Milestone 8)***
  - Produce and deliver wide width experimental alloy based on evaluation of work done in FY 2018 on medium width sheet ***(Milestone 9)***
  - Produce and evaluate automotive door inner and outer panels ***(Milestone 10)***

Summary

- Project leverages broad industry and academic participation:
  - 19 participants doing substantial technical work, including 3 U.S. Auto OEMS, 7 industry subrecipients, 2 vendors, 5 universities, and 2 national laboratories (via LightMAT)
- The holistic approach, with the exception of raw ingot production, includes every major step of the process from:
  - alloy chemistry and sheet rolling process development
  - new coil applied coatings and warm forming lubricants
  - warm forming and joining process development
  - paint shop pretreatment process developed to work with Mg, Al, and steel
  - final cost, weight, and performance evaluation at end of project
- Significant technical accomplishments over this period include:
  - Established a baseline cost model for current Mg sheet application ***(Milestone 2)*** and identified most cost effective rolling process as well as defining technical cost of a current steel door to use as a baseline comparison for cost of Mg door panel
  - Investigated several potential low cost Mg alloy chemistries, identified 3 alloys for further evaluation and development, and down-selected 1 alloy ***(Milestone 3)*** compatible with low cost twin roll strip casting process for immediate development and evaluation
  - Made good early progress on developing new cost effecting pretreatments, forming lubricants, and corrosion coatings to work with commercially available ***ZEK100*** alloy

Acknowledgement

Acknowledgment: "This material is based upon work supported by the Department of Energy, Office of Energy Efficiency and Renewable Energy (EERE), under Award Number DE-EE0007756."

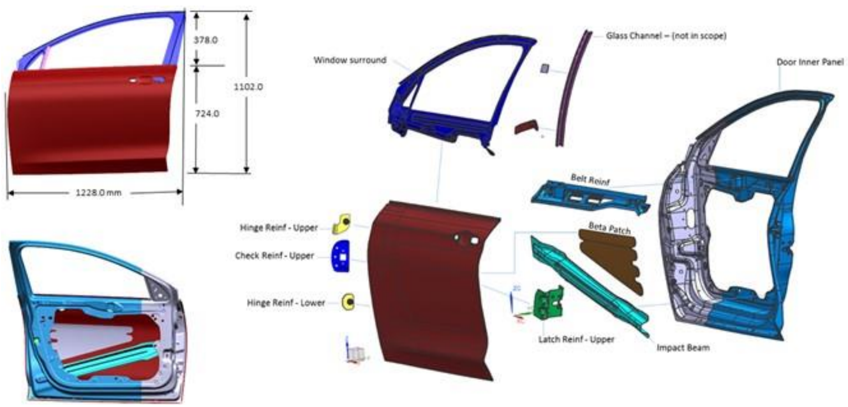
Technical Back-Up Slides

Technical Accomplishments

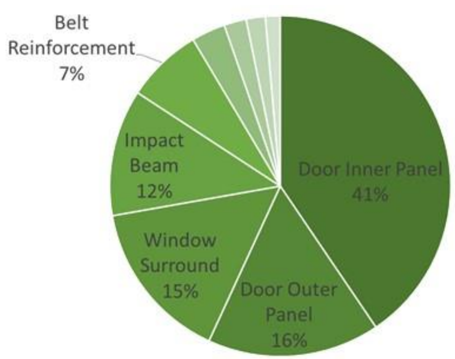
Technical Cost Guidance

- Defined technical cost of current steel door to use as baseline comparison for cost of Mg door
  - Material cost is most significant cost element
  - Engineered scrap rate on door inner panel is significant

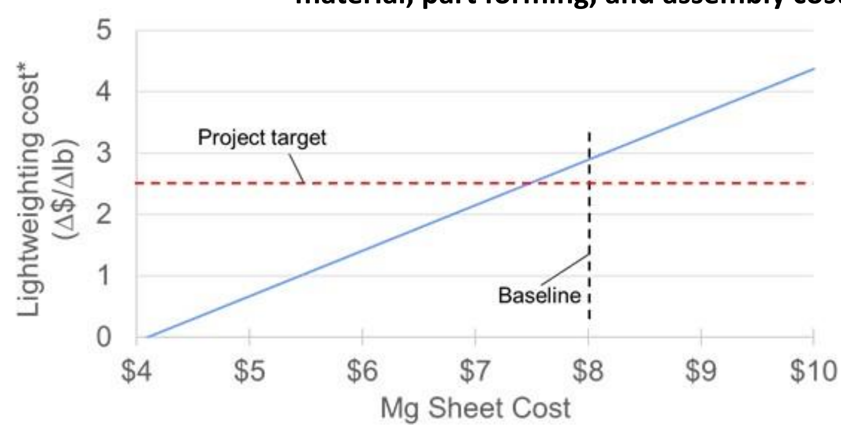
Cost breakdown of steel baseline door by material, part forming, and assembly costs.



Benchmark steel door from the Chrysler 200.



Breakdown of total part production costs by parts in the door design.



*(Mg cost – steel cost)/(steel weight – Mg weight)

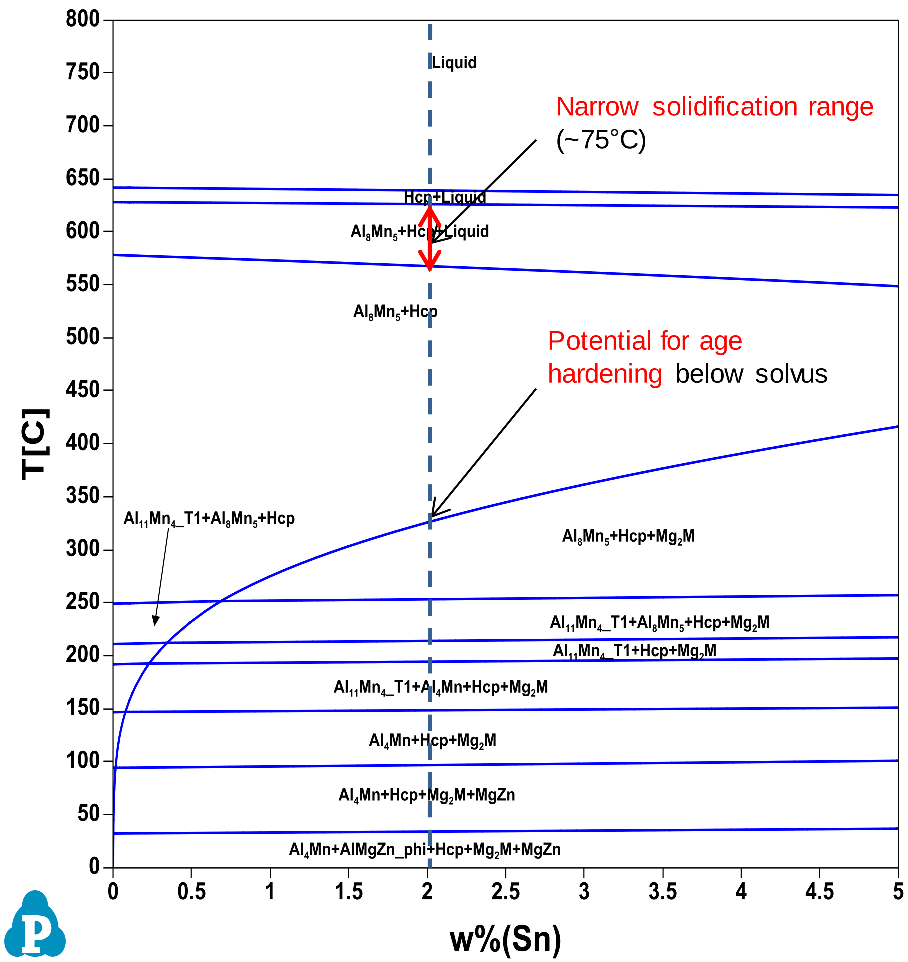
Lightweighting cost sensitivity for a Mg door inner compared to a steel baseline door inner. The baseline Mg sheet cost for the analysis is $8/kg. The project target is $2.50/lb saved, as shown by the dashed red line.

Technical Accomplishments

Alloy and Sheet Processing Development

- Thermodynamic calculations of potential new alloys allowed optimization of composition and estimation of solution treat time - *examples shown are <u>not</u> the selected alloy*

Mg – Sn with 1% Al, 1% Zn, 0.4%Mn



Thermomechanical Processing

POSCO-recommended Alloys

Alloy	Composition	Homogenization Temperature Range	Rolling Temperature Range
ATZ310	Mg-3Al-1Sn-0.3Zn-0.4Mn	386°C - 578°C	284°C - 578°C
AT21	Mg-2Al-1Sn-0.3Mn	334°C - 613°C	334°C - 613°C
AX10	Mg-1Al-0.3Ca-0.4Mn	493°C - 537°C	192°C - 493°C

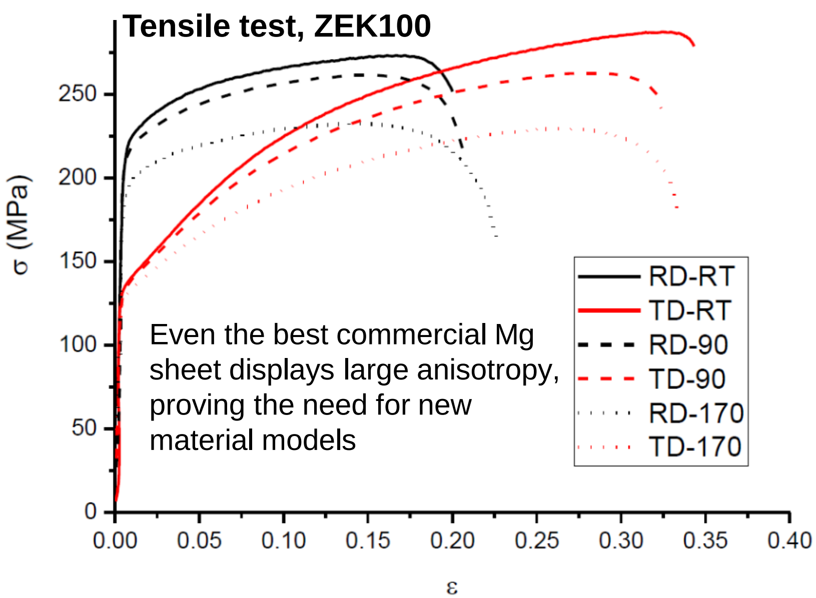
USAMP Team Alloys

Alloy	Composition	Homogenization Temperature Range	Rolling Temperature Range
ZE20	Mg-2Zn-0.2Ce-0.3Mn	215°C - 540°C	215°C - 404°C
ZT31	Mg-2.5Zn-0.5Sn-0.4Mn	233°C - 510°C	233°C - 429°C
TXZ211	Mg-2Sn-0.5Ca-0.5Zn-0.4Mn	~500°C	230°C - 426°C
AX52	Mg-5Al-2Ca-0.4Mn	~500°C	355°C - 500°C
AX10	Mg-0.5Al-0.3Ca-0.4Mn	448°C - 559°C	~200°C - 448°C
TAZ211	Mg-2Sn-1Al-1Zn-0.3Mn	325°C - 567°C	325°C - 567°C

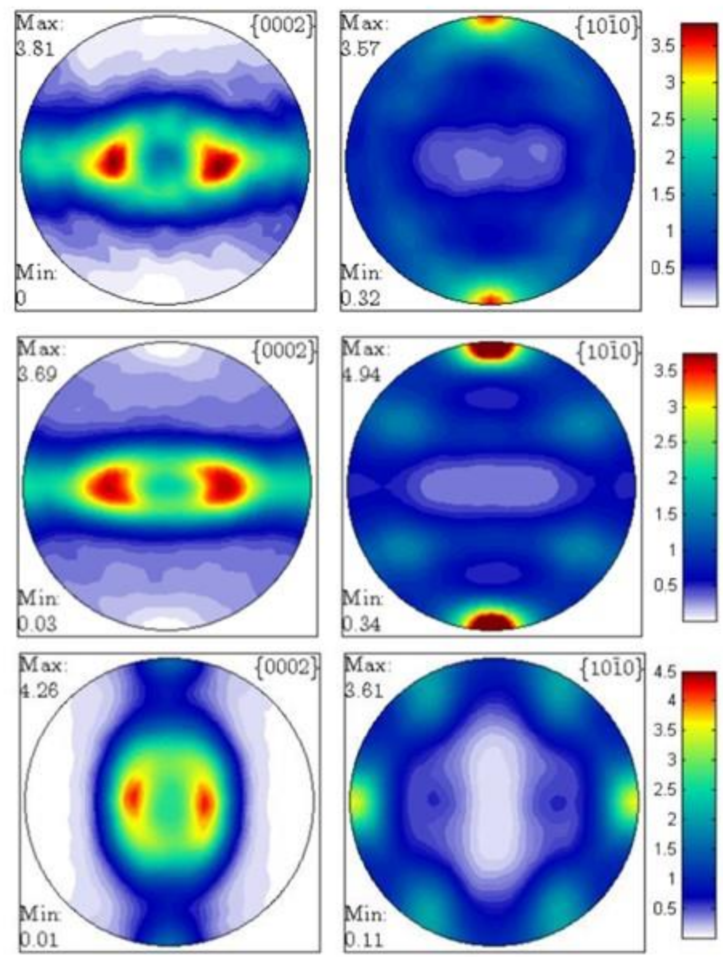
USAMP Technical Accomplishments

Alloy and Sheet Processing Development

- Characterization techniques and modeling approaches are being developed and validated on ***ZEK100*** (soon to shift to ***E-Form Plus***)



Evolution of texture by deformation, ZEK100 (high-energy X-ray diffraction)

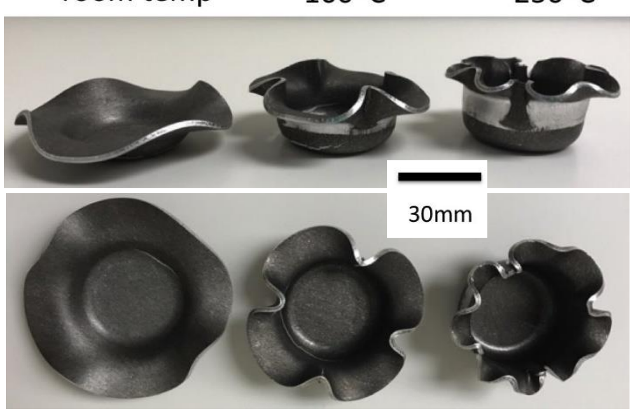


Initial texture

After tension along RD (~8.5%)

After tension along TD (~10.5%)

room temp 100ºC 250ºC

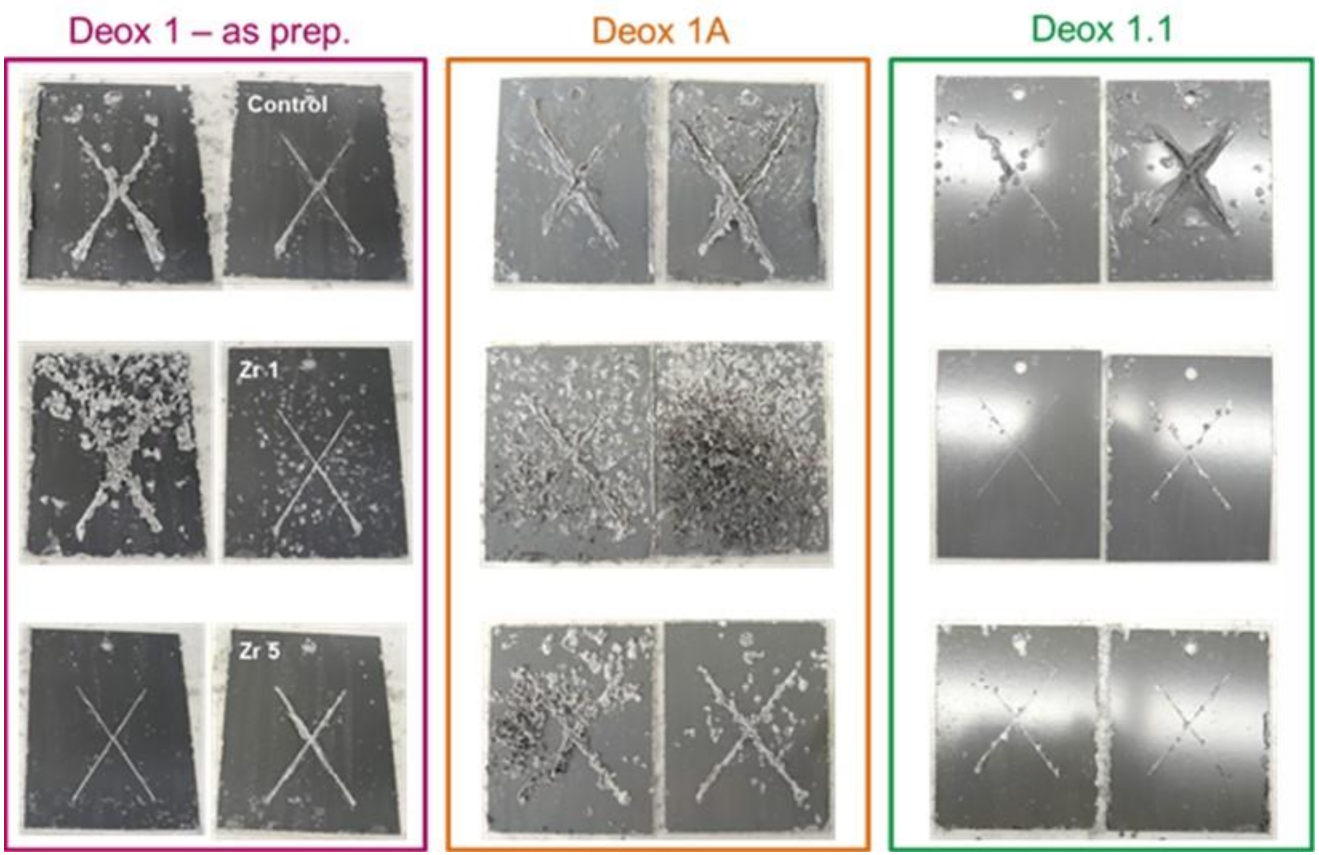


Deep draw cup tests of ZEK100 at different temperatures display relative lack of formability at low temperatures

Technical Accomplishments

Paint Shop Applied Pretreatment Development - PPG

- Modified Deox 1 chemistries for further improved performance with ***ZEK100***



ZEK100 panels treated with an alkaline cleaner followed by either i) the original Deox 1 formulation, ii) Deox 1A only, or iii) prototype Deox 1.1. All panels were then pretreated and electrocoated before scribing and exposure to one week of continuous salt fog. Top row: cleaners and electrocoat only without PT (Control). Middle row: Zr 1 PT. Bottom row: Zr 5 PT.